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A review on air emissions assessment: Transportation

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ABSTRACT

The greenhouse gas emissions footprint and global warming potential are widely-used for environmental sustainability studies. However, environmental sustainability is far wider than carbon emissions and climate change. This review aims to highlight the importance of considering air pollutants in optimisation studies and evaluate the limitation of the current assessments for air emissions, particularly in relation to transportation. The source of air pollutants is firstly overviewed with special attention on non-stationary sources, freight and sea transportation. The type of measurement to obtain the emission data and the available optimisation models on transport mode choice selection were then summarised. The strengths and Weaknesses' have been indicated. The identified gap includes greenhouse gas and air pollutants not being evaluated simultaneously and the interaction between the different pollutants are not being adequately considered. A better assessment framework and impact categories classification are consequently required. The summarised assessment model of transportation mode choice shows that the current viewpoint on low emissions, green or environmental sustainability options refers to carbon dioxide as a part of greenhouse gas. Attention towards a better emission assessment and management has been supported in this study through critical discussion. The next step of this work is to develop a methodology to measure greenhouse gas and air pollutants simultaneously by considering the synergistic effect and the discussed limitation. It is important for minimising the potential of footprint shifting and poor decision-making.

1. Introduction

Air emission reduction plays a significant part in supporting sustainable development. Greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and natrium trifluoride (NF_3) (UNCC, 2018) are known to contribute to climate change. The global concern of anthropogenic emission has been principally focused on GHG compared to the air pollutants. GHG are subject to global agreements and taxation, whereas air pollutants are governed by local legislation and policy. GHG and the air pollutants share some of the components (e.g. O_3 and VOCs), but the evaluation perspective is different. Air pollutants such as carbon monoxide (CO), contaminants (e.g. Pb), volatile organic compounds (VOCs), sulphur oxide (SO_x) and nitrogen oxide (NO_x) (EPA, 2016) have an instantaneous impact on the environment and human health. They contribute to the formation of secondary pollutants (Harrison, 1986) such as O_3, particulate matter (PM) and in the atmosphere cause the formation of haze or smog. Air pollutants can impair visibility and produce acidification. Fig. 1 summarises the sources, type of pollutants and pollution (haze, sulphurous and photochemical smog).

The article published by the European Environment Agency (EEA, 2013) stated that initiatives that protect the environment (air emission) should be towards an overall system rather than the choice of either clean air or mitigating climate change. In optimisation assessment and performance analysis, it is commonly noticed that environmental sustainability has been simply represented by CO_2 emission/GHG/Carbon footprint. The significance of air pollutants, especially in energy planning and freight transports

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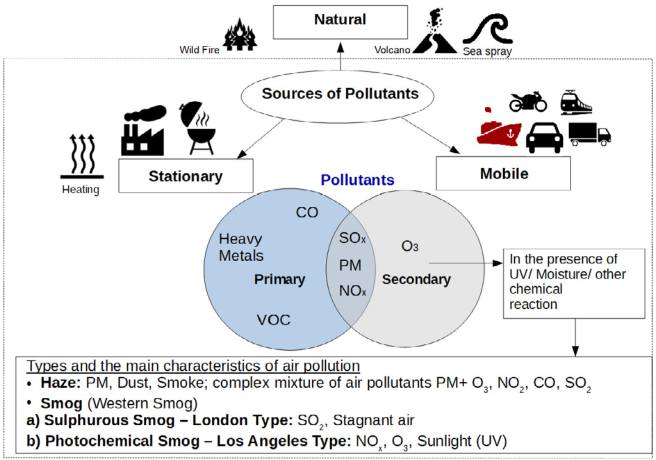

Fig. 1. The sources and the types of air pollutants. For more information about Chinese haze see Zhang and Samet (2015).

mode choice is relatively less established. Münster et al. (2015) optimised the waste to energy (WtE) handling solutions by only considering the GHG emissions (CO_2, CH_4, N_2O) for the environmental component. Carbon Emissions Pinch Analysis (Foo and Tan, 2016) and Greenhouse Emission Pinch Analysis (Kim et al., 2016) were proposed for emission reduction. The Carbon Emissions Pinch Analysis has also been applied to transport sectors (Walmsley et al., 2015). Different types of models or methods have been put forward for the selection of freight transport mode. The optimisation model usually considers criteria such as the cost, reliability, flexibility, frequency, transportation time/speed, safety/quality and environmental sustainability. However, based on the environmental sustainability criteria summarised by Bask and Rajahonka (2017), it is equivalent to GHG or CO_2 emissions. Air pollutants form a significant part of transportation planning. They could considerably affect the result of low emission/environmentally sustainable solution and hence more attention is required.

The reduction of air pollutants is often promoted/proposed as the co-benefits of the GHG mitigation. This has been highlighted by Zhang et al. (2016) with the explanation that the sources of emissions are the same. However, this relationship does not apply in all circumstances. Schmale et al. (2014) summarised the importance of improving air quality and mitigating climate changes simultaneously. The importance of incorporating air pollution measurement while developing climate change control policies was also highlighted by Slovic et al. (2016). The individual GHG and air pollutants assessment including the impact assessment, relationship assessment, future scenario prediction and mitigation strategies are considered as matured or well developed. However, it remains an open question whether the available model/methodology is sufficiently comprehensive for an optimal emission solution, as GHG and air pollutants are not always assessed simultaneously. A review study which provides the current state-of-art, critically assessing the strengths and limitations of the available air emission assessments are lacking.

Transportation networks are at the heart of the supply chain and are the foundation of a country's economy. The transportation sector is one of the largest contributors to air emissions, both GHG and air pollutants. It represents 26% of the total US GHG emissions (EPA, 2017a,b) and 23.2% of EU-28 (Eurostat, 2016a). The shares of pollutants (CO, VOC, NO_x, SO_x, PM_{10}, $PM_{2.5}$) range from 13.14% to 57.41%, and it is the main emitter for NO_x (EEA, 2016a). This review aims to highlight the importance of considering air pollutants for decision making and evaluate the limitation of the current assessments for air emissions, particularly on transportation.

Almost 90% of the European union's external freight and 40% of its internal freight is moved by sea (EU, 2014). Shipping emissions are comparatively less regulated (EC, 2017) and are very likely to continue to increase in the future (business as usual) due to the increasingly global scale trade (EEA, 2013). In this study, the source of air emissions (GHG and air pollutants) are firstly overviewed with the focus on the non-stationary sources particularly freight and sea transportation. The type of emissions measurement is summarised with the discussion of their pros and cons. The available optimisation model for freight transport mode choice selection and the limitation in incorporating the second dimension of sustainability, the environmental criteria, are then discussed. This is important as the strategy of shifting 30% of transport over distances of 300 km or more from road transport modes to transport modes with lower CO_2 emissions has been proposed (Eurostat, 2017). The intensive review identifies the strength and the limitation of assessment models to support an appropriate decision making (achieving optimal connectivity of freight transport mode) with the minimal potential of footprint shifting.

2. The source of air emission

An understanding of the sources of emissions is important for mitigation assessment. Fig. 2 shows summarised information on the source of GHG emissions contributing to climate change. In general, electricity (29%) and transportation (27%) are the main contributors to GHG (see Fig. 2). More recent data by EIA (2017) shows transportation overtaking electric power as the biggest US CO_2 emitter. Transportation also represents the second largest contributor (25.8%) of EU-28 (EEA, 2017). Breaking down the components of GHG, the main emission source of CH_4 is from the natural gas and petroleum systems (Fig. 2b). Up to 75% emission of N_2O is from agriculture and soil management (Fig. 2c). The reported results (major contributors) are consistent with global statistics (IEA, 2012). Over 60% of CH_4 and 40% of N_2O are from human activities (EPA, 2017a,b). Based on Fig. 2a, CO_2 has the major role in the overall GHG emissions as the source of emission shows a similar trend (1st Electricity, 2nd Transportation). 76% of the global GHG emission is reported as being contributed by CO_2 (IEA, 2017). GHG and CO_2eq is the common term and unit used for describing the gaseous contribution to climate change. In contrast, it is comparatively complex to have a common term or unit for air pollutants. It involves a large variety of pollutants and the impact category is complex. It is perhaps possible to have a common term for the air pollutants that produce haze/smog formation. A composite term or unit, despite having some deficiencies (USAID, 2014) on the accuracy of representation (in assigning the weighting factor), it facilitates the optimisation assessment and simultaneous assessment (air pollutants with GHG) by having multiple attributes in a composite form as well as being easy for communication.

The source of air pollutants can be generally divided into three major categories namely mobile, stationary and natural as shown in Fig. 1. Fig. 3 shows the 7 types of air pollutants emission by source sector. The largest source of VOCs is natural emissions from vegetation etc with the labelling of biogenic (Fig. 3-in Green). Most of the anthropogenic CO, Pb and NO_x emissions are contributed by non-stationary sources, mobile/transport (Fig. 3- Dark Blue). Transportation has also been reported as the main NO_x contributor in EU (EEA, 2016a). The information presented in Figs. 2 and 3 highlights the important roles of transportation in mitigating air emissions.

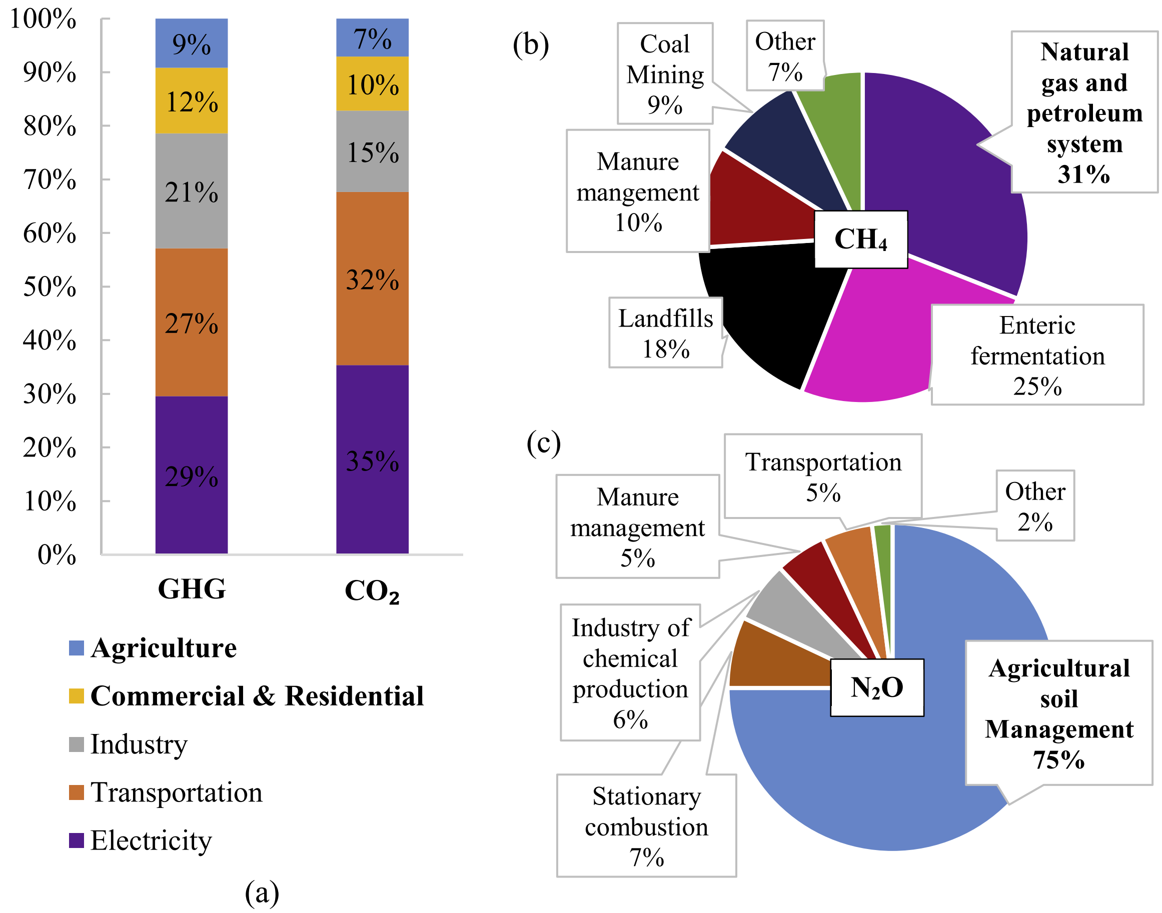

Fig. 2. The GHG emission by source sector in US, 2015, last updated on 14 April 2017. Data extracted from EPA (2017a,b).

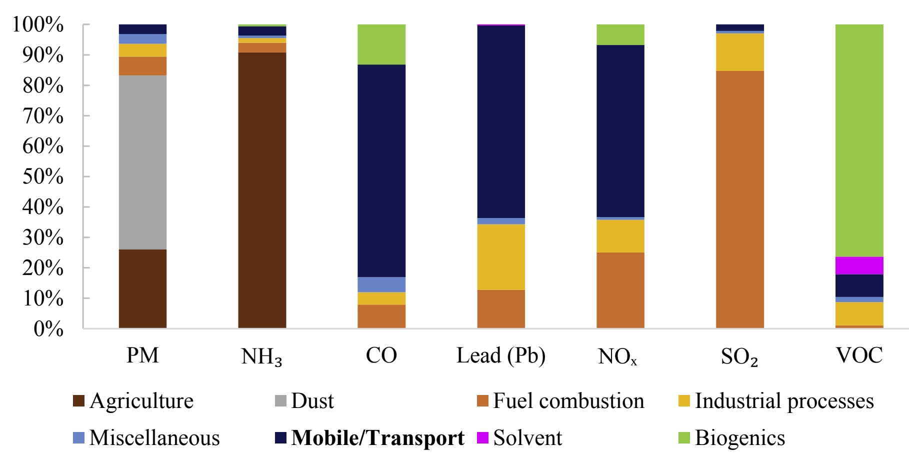

Fig. 3. The pollutant emission comparison by source sector in the US, 2014 with the last updated on 28 September 2016 in the air emissions inventories by EPA. Adopted from EPA (2016). Dust refers to the construction, paved road and unpaved road dust. Biogenic emission sources refer to the emission from vegetation and soil, volcanic emissions, lighting, sea salt. etc.

2.1. NON-STATIONARY: transportation

Environmental related research, especially dealing with the air pollution issues of transportation, has mainly focused on land transportation. Automobiles have been subject to increasingly tighter regulation which have resulted in alternative fuels such as low sulphur, hybrid vehicles, hydrogen energy system (Salvi and Subramanian, 2015). Regulations have been introduced to reduce the emissions contributing to air pollution as well as climate change. The shares of different transports in contributing to the emission of pollutants is shown in Fig. 4. The EEA (2011) reported that the most significant reduction pollutant emissions have been recorded for road transportation. However, as shown in Fig. 4, it still remains the main issue of transportation particularly NO_x, CO and Non-Methane Volatile Organic Compounds (NMVOC), as well as GHG. The pollutants (NO_x, SO_x, PM_{10}, $PM_{2.5}$) by sea transportation

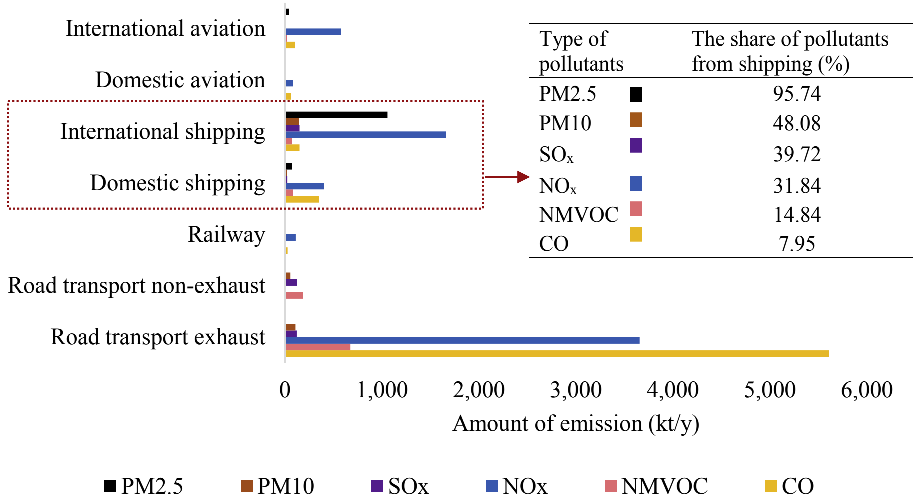

Fig. 4. The sources of emission from transportation and the shares of shipping. Dataset extracted from EEA (2016b) and the explanatory text (e.g. the unit) by Eurostat (2016b). In this study, shipping refers to transport of goods by water transport instead of as a common term of transporting goods.

(shipping) are the second largest contributor (Fig. 4) although the GHG emission is lower than produced by aviation (Fig. 5). This suggests that the transportation mode with the lower GHG emission is not equivalent to lower air pollutants.

Based on the information from the Environmental Protection Department (2017), maritime passenger and freight transport emissions remained approximately constant. Shipping is responsible for 95.74% of $PM_{2.5}$, 48.08% of PM_{10}, 39.72% of SO_x and 31.84% (2.07 Mt) of NO_x emissions from all EU transportation (Fig. 4). It is the biggest source of PM, SO_x and the second largest contributor of NO_x. The IMO (2014) also stated that shipping has contributed to the considerable amount of NO_x (15%), SO_x (13%) emission and solid particles (11%) of the global anthropogenic sources of emissions reported in the IPCC 15th Assessment Report. NO_x is one of the precursors for smog and particulate formation. NO_x from ship emissions in the East Asia region has almost doubled from 1.49 Mt in 2001 to 2.8 Mt in 2013 (Liu et al., 2016). A more recent estimation in 2014 is 5–6.9 Mt of NO_x (IMO, 2014). In highly developed countries, the sulphur content in the fuel of the ship can be up to 1,000 ppm and in the developing countries as high as 35,000 ppm, which is considerately higher than the fuel for cars (Wan et al., 2016). Other activities such as ship scrapping also contribute to the pollution (Wan et al., 2016). It has been forecast that emissions by shipping will surpass emissions from the all land-based sources in Europe by 2030 (Gagatsi et al., 2016).

However, there is a contrasting interpretation of ship emissions as a ship can carry a lot of goods/passengers at once. By a ton of goods (capacity), the emission is often lower than other road transport e.g. truck (Boer et al., 2017), and it is considered as a more sustainable freight transport system. Non-stationary sources of air emission are subjected to more variables or uncertainty in assessment. Various factors (distance etc) need to be considered in defining the optimal transportation mode or in shifting the transportation mode to mitigate air emissions. Emission abatement has to begin with an understanding of the sources as well as the pollution level.

3. Type of air emission assessments and the limitation

This section evaluates the air emission assessment of transportation in three different stages. Starting from the measurement methods of air emission (Stage 1) for optimisation, the optimisation model to identify the optimal freight transportation mode (Stage 2) and way forward (Stage 3). Fig. 6 illustrates the framework of this

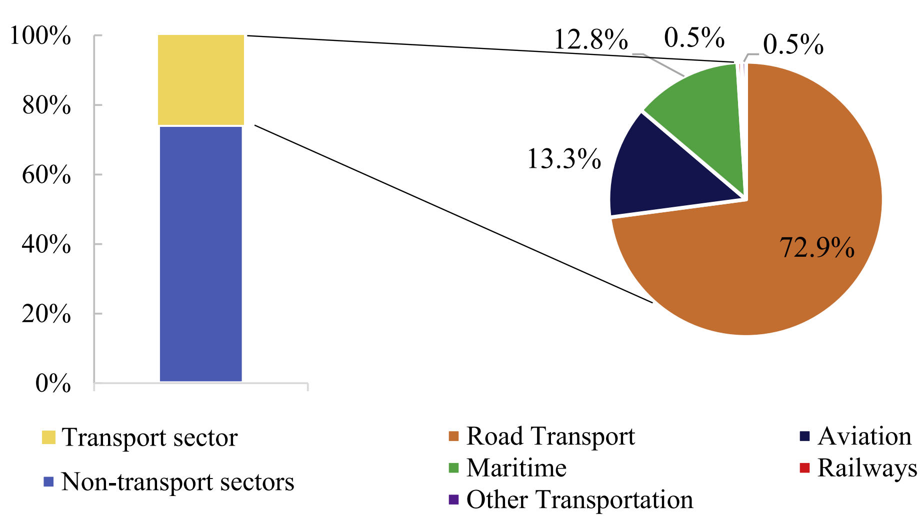

Fig. 5. The GHG emissions by sources from the transport and non-transport sector in EU. Information extracted from EEA (2017).

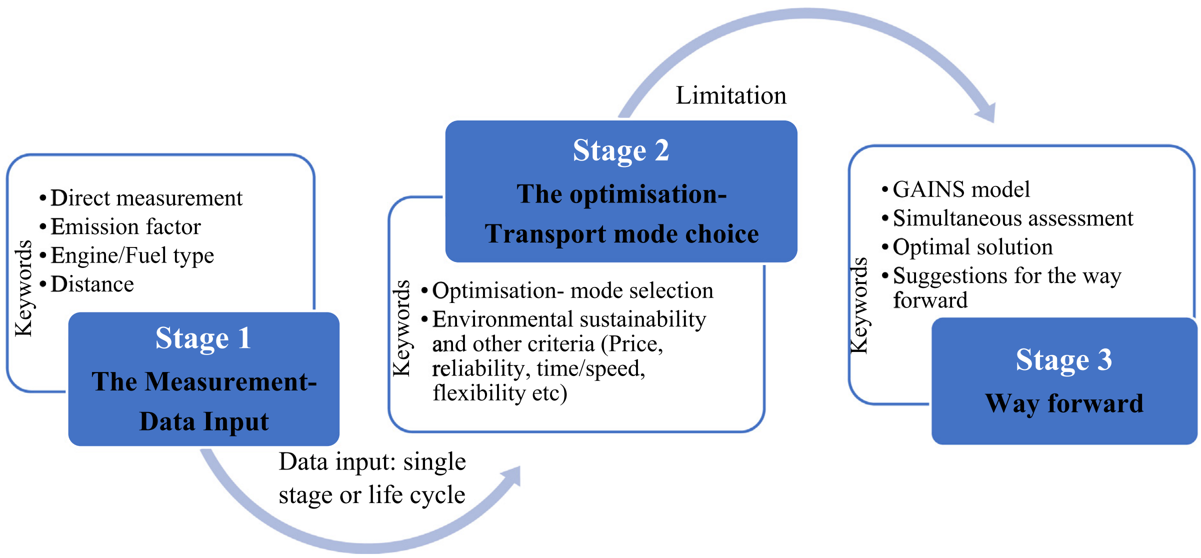

Fig. 6. The framework for evaluating the air emission assessment and its limitation.

study. The keywords of each stage are presented in a white box with a blue line.

3.1. *The measurement*

Studies that have measured air emissions from transportation have been based on a wide variety of methods, as discussed in the following paragraphs. In this study, the methods of identifying the air emissions were divided into primary (direct measurement, direct measurement at source point) and secondary (emission factor, modelling) as illustrated in Fig. 7. Table 1 shows the summarised characteristic of the respective methods. Both approaches have different advantages and disadvantages, however, secondary data is more widely applied as the data input due to its simplicity and availability. The accuracy and representation of data input have a decisive role in the life cycle assessment (LCA) and optimal freight transport mode selection.

There are different types of direct measurement, principally comprising of sampling and analysing, and usually associated with land-based transportation. Remote sensing/roadside measurement and tunnel studies, on-road (chase) measurements are examples of sampling approaches to direct measurement for vehicle (Franco et al., 2013). This direct measurement has the advantage of measuring the secondary pollutants and in a real-world situation. Direct measurement can also be conducted in an experimental controlled condition in the laboratories (engine and chassis dynamometer studies) (Franco et al., 2013). One of the examples is the vehicle's test to determine their official emission values in relation to a reference fuel consumption (Giechaskiel et al., 2016). The analysis stage can be done by a real-time optical detector, real-time dust monitor, condensation particle counter and local micrometeorology ultrasonic anemometer. It can also be analysed using gravimetric determinations, such as inductively coupled plasma atomic emission spectroscopy, high-performance liquid chromatography, inductively coupled plasma mass spectrometry, ion selective electrode, thermal or optical carbon analyser. Direct measurement has the advantages of lower uncertainty but requires a longer time and a higher cost with the limitation that the source of emission is not specified. The source detection can be carried out by positive matrix factorisation as performed in the study of Pérez et al. (2016) to appoint the type and the source (Merico et al., 2017) of the pollutants.

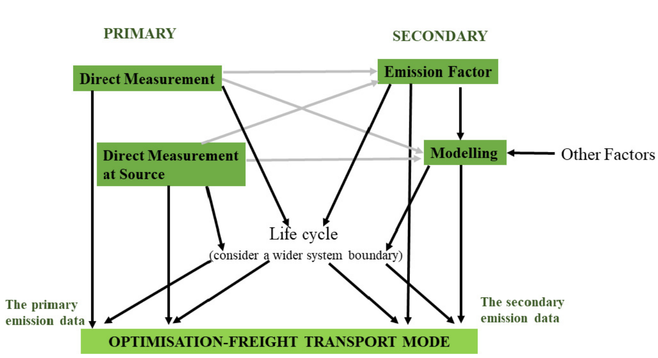

Fig. 7. Type of measurements of identifying the air emission.

The common direct measurement at source point (onboard measurement) is a portable emissions measurement system (PEMS). It usually comprises of gas analysers with heated sample lines directly connected to the tailpipe, providing data including emissions, fuel consumption, vehicle speed/driving behaviour, engine speed and temperature (Franco et al., 2013). The emission data is relatively accurate (according to on the road condition) but the reproducibility is low due to the variety of external factors.

Modelling can be used to run scenarios, to test theories, to understand the dispersion (Kukkonen et al., 2016) and environmental impact under different emission rates, weather and development scenarios (Thongplang, 2016). Assessment involves applying an existing set of data and making assumptions and adjustment by incorporating other data (additional factors). The emission of the hypothetical situation can be assessed before it occurs. An example of a common air quality model is the atmospheric dispersion model such as CALPUFF (Fallah-Shorshani et al., 2017), AERMOD, CALINE4, VEPM (Thongplang, 2016) and land use regression models (Ghassoun and Löwner, 2017). The models also can be used to quantify the emission and are highly reliant on accurate inputs. For example, PriyaDarshini et al. (2016) improved the emission inventory by including the PM_{10} concentration from road dust with the use of AERMOD and receptor modelling. The merits of applying data input processed by modelling are low cost and speed, and offer a platform to adjust/fine tune the emission which is otherwise

Table 1
Comparison between the approaches to obtain the input data for LCA and optimisation study.

Parameters	Input Data for Emission Assessment- The Measurement Method			
	Primary (Experimental)		Secondary	
	[a]Direct measurement (DM)	[b]Direct measurement at the source point	Emission factor (EF)	Modelling
Uncertainty	Lower	Lower	[c]High	[c]High
Time taken (Analyse/Calculate)	Longer	Shorter than DM	Short	Short
Cost	Higher	High	Lower	Lower
The Other Characteristics				
Merits	Measure the secondary emissions/pollutants Could be real-time display	Consider the real-world performance. Real-time display	Simplicity	Predict alternative situations/ scenario by include different factors e.g. wind (Meteorological)/Secondary pollutants
Demerits	All the emission in the air e.g. including sea spray is included, source detection step is needed. [e]Do not represent the real-world situation.	[d]Calibration is needed. Could vary by device. Low reproducibility	A secondary pollutant is usually not included. [f]Sensitive/localised, need to update from time to time	Rely on accurate input Localised

[a] Two different type of direct measurement, refer to the explanation in text.
[b] Refer to the onboard measurement (an e.g. device attached to the transport mode).
[c] Depend on the scope and boundary in determining the EF, suitability/compatibility (e.g. type of engine) and rely on accurate input (See grey line in Fig. 7).
[d] EURAMET (2017).
[e] The limitation of direct measurement conducted in an experimental controlled condition at the laboratories.
[f] Refer to text for detailed explanation.

difficult to quantify using the conventional approach of activity information and emission factor (EF).

Emission factor (EF) is one of the most common methods to obtain input data for assessment studies due to its simplicity and is summarised in Table 1. The uncertainty is high as the EF is usually cased specifically with some factors being excluded. Tables 2 and 3 show the emissions factors (GHG and air pollutants) of different freight transportation modes. The wide range of emission factors among the same mode is due to the diverse assessment boundary and approaches (e.g. tailpipe emission, combustion emissions, evaporative emissions, wear processes, other emissions like heavy metals and PAHs from leakage of engine oil) (Klein and Fortuin, 2014), technology development, fuel (e.g. renewable energy) as well as engine efficiency. The real-world condition e.g. on the road (gradient), ambient and driving conditions can vary over a wide range causing the EF to be higher than EF measured in the laboratory.

Table 2
The GHG emission factor of different freight transports (Road, sea, inland and rail).

Mode of Transportations	Emission factor (g/t-km) of GHG Round off to 4 decimal places (D.P)			
	CO_2eq[a]	CO_2	CH_4	N_2O
Road/Truck (Delcampe, 2012)		110		
Truck >32 t (EEA, 2014)		102	0.001	0.004
Truck-Lowest (OECD, 1997)		127		
Truck – Highest (OECD, 1997)		451		
Truck (Facanha and Horvath, 2007)		116.1967		
Truck-Trailer (Boer et al., 2017)	192			
Truck >20 t (Boer et al., 2017)	337			
Sea (Delcampe, 2012)		7		
Sea (OECD, 1997) Lowest		30		
Sea (OECD, 1997) Highest		40		
Sea (Boer et al., 2017)	58			
Inland (Delcampe, 2012)		49		
Inland (EEA, 2014)		53	0.007	0.002
Inland (Boer et al., 2017)	51			
Rail (Delcampe, 2012)		35		
Rail (EEA, 2014)		52	0.004	0.002
Rail (OECD, 1997) Lowest		127		
Rail (OECD, 1997) Highest		451		
Rail (Facanha and Horvath, 2007)		24.8549		
Rail-Electric, Medium length (Boer et al., 2017)	39			
Rail-Diesel, Medium length (Boer et al., 2017)	73			

[a] CO_2eq, CO_2 equivalent emissions in this study refer to CO_2, CH_4 and N_2O. Unit Conversion: 1 mile = 1.60934 km, rounded off to 4 decimal places.

Other factors that contribute to the high uncertainty of applying EF as input data include emissions deterioration over the useful life of the vehicles, emissions characteristics varying among identical engines, as well as the impact of cold and hot start (engine) (JRC, 2017). The engine temperature during cold-start is sub-optimal owing to lower temperatures of three interrelated thermal masses: the main engine block, the engine coolant and the lubricant oil (Roberts et al., 2014). There is a 13.5% increase in fuel consumption during cold-start compared to hot-start (Zare et al., 2017). The fuel consumption on cold start and hot start of the engine reported by Roberts et al. (2014) are approximately 2.2 kg/h and 1.8 kg/h. A cold start engine causes incomplete combustion. The higher viscosity of the engine lubricant due to its low temperature increases friction losses and decreases thermal efficiency (Zare et al., 2017). To overcome high friction losses and to maintain brake power output, more fuel has to be injected into the cylinder during cold-start. Yao et al. (2009) reported that the emission factors (g/km) of CO and HCs increased significantly during cold-start driving. However, the difference of NO_x emissions between the cold- and hot-start cycles was not pronounced. The general practice in selecting the suitable EF of transport is merely by matching the main parameter such as capacity (>32 t or 20 t truck) or type of energy/fuel (e.g. electric or diesel), sometimes by country (regionalised or localised condition). It suggests more attention and understanding are needed in determining the representable EF prior to assessment.

The EF presented in Tables 2 and 3, does not suggest which freight transportation mode provides lower emissions. Other than the high variation of reported data, more importantly, distance has a substantial effect on the emissions. As an example, Boer et al. (2017) reported the emission factor for a truck = 337 g/tkm

Table 3
The air pollutants emission factor of different freight transports (Road, sea, inland and rail).

Mode of Transportation	Emission factor (g/t-km) of air pollutants (Round off to 4 D.P)							
	CO	NMVOC	VOC	HC	NO_X	PM_{10}	PM	SO_2
Road/Truck >32 t (EEA, 2014)	0.18	0.016	0.018		0.57	0.01		0
Truck-Lowest (OECD, 1997)	0.25		1.1	0.3	1.85		0.04	0.1
Truck - Highest (OECD, 1997)	0.4		1.1	1.57	5.65		0.9	0.43
Truck (EEA, 2011)	0.2		0.1		0.92		0.02	
Truck (Facanha and Horvath, 2007)	0.3728				1.5969	0.2175		0.0932
Truck-Trailer (Boer et al., 2017)					2.2	0.031		0.2
Truck >20 t (Boer et al., 2017)					1.1	0.019		0.35
Sea-Lowest (OECD, 1997)	0.018		0.04	0.04	0.26		0.02	0.02
Sea-Highest (OECD, 1997)	0.2		0.11	0.08	0.58		0.04	0.05
Sea (EEA, 2011)	0.03		0.01		0.33		0.03	
Sea (Boer et al., 2017)					0.99	0.023		0.087
Inland (EEA, 2014)	0.82	0.267	0.274		1.24	0.058		0.274
Inland (EEA, 2011)	0.03		0.03		0.6		0.04	
Inland (Boer et al., 2017)					0.065	0.025		0.054
Rail (EEA, 2014)	0.07	0.025	0.029		0.3	0.01		0.014
Rail-Lowest (OECD, 1997)	0.02		0.08	0.01	0.2		0.01	0.07
Rail-Highest (OECD, 1997)	0.15		0.08	0.07	1.01		0.08	0.18
Rail (EEA, 2011)	0.03		0.04		0.14		0.01	
Rail (Facanha and Horvath, 2007)	0.2610				0.4598	0.031		0.074
Rail-Electric, Medium length (Boer et al., 2017)					0.037	0.002		0.021
Rail-Diesel, Medium length (Boer et al., 2017)					0.787	0.024		0.075

(CO_2eq), 1.1 g/tkm (NO_x), 0.019 g/tkm (PM_{10}), 0.35 g/tkm (SO_2) while maritime = 58 g/tkm (CO_2eq), 0.99 g/tkm (NO_x), 0.023 g/tkm (PM_{10}), 0.087 g/tkm (SO_2). This suggests that a truck has higher emissions than a ship except for PM_{10}. However, even having the identical place of departure and arrival, the distance/route travelled by truck, rail and ship are different. One of the examples is Rotterdam and Genoa as presented in Fig. 8. The contrasting results (Fig. 8) suggest the complexity in assessing the non-stationary source of emissions and challenges in defining a sustainable freight transport mode. The truck has a better performance in terms of PM_{10} and NO_x, but the ship has lower CO_2eq and SO_2 emissions. This highlights the importance of simultaneous assessment of GHG and air pollutants for proper decision making, as low GHG emissions do not represent low emission for other pollutants. There is currently still a research gap in defining an optimal air emission (environmentally sustainable) solution. A methodology to achieve fair comparison/weighting in assessing the impact of GHG and air pollutants is needed. This issue is illustrated and discussed in detail in the next sections. The strengths and limitations of the available optimisation models for freight transportation mode are presented.

3.2. Transport mode choice

There is rising interest in promoting an environmentally sustainable development of transport. Mode shift (e.g. truck to rail), multimodal and intermodal transport are among the approaches that adjust the transport mode to enhance the sustainability of the supply chain. Multimodal freight transportation is the transportation of goods by a sequence of at least two different modes of transportation (SteadieSeifi et al., 2014). Intermodal freight transport involves multiple modes of transportation similar to multimodal, with the main differences being the non-handling of the

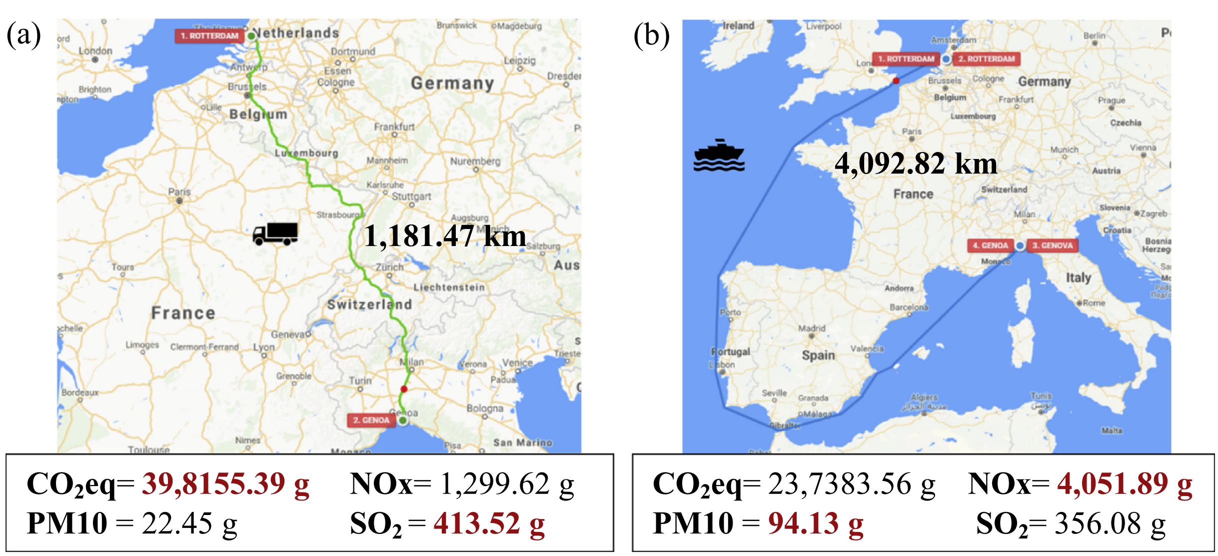

Fig. 8. The distance between Rotterdam and Genoa by (a) road transport (b) sea transport and it emission (based on the reported emission factors by Boer et al. (2017). The presented emission is based on per t of transported goods. The SO_2 results are based on the emission factor of low-sulphur diesel according to Sulphur Emission Control Area (SECA) standard. The SO_2 emission could be 35 times higher as some of the developing countries permit fuel with higher sulphur content (Wan et al., 2016). Graphic by SeaRates LP (2018), Google maps.

freight itself when changing modes (SteadieSeifi et al., 2014). The transport mode selection is highly dependent on the assessment/optimisation perspective, for example looking at the problem from the perspective of the customer or logistics provider. This section summarises the studies in selecting the optimal freight transport mode, using a holistic view of the current state of research. Table 4 presents the studies which consider the environmental sustainability as one of the selection criteria. The studies which analysed/optimised the supply chain network without the consideration of different transport mode (as one of the variable) were excluded from Table 4.

The collected papers (a total of 24) have been divided into three categories. The lead rows present the environmental criterion represented by CO_2 only, followed by the studies that consider other environmental issues (e.g. air pollutants) and finally the non-simultaneous assessment where the environmental criterion is measured after the selection. A few papers, such as López-Navarro (2014) highlighted that the integration of environmental issues into freight transportation planning is little explored. The review by Bask and Rajahonka (2017) states that the discussion on environmental sustainability with the other transport mode selection criteria is still a rather new and emerging topic. The environmental sustainability assessment is important as the common assumption in freight transportation, such as 1) rail and vessel-based intermodal freight systems emit less CO_2 than truck only freight systems (Kim and Van Wee, 2014), 2) sea transport is always preferable to road transport, 3) intermodal is always best in term of the environment (López-Navarro, 2014), are not always true.

Based on the collected studies in Table 4, the trend of defining the environmental criterion tends to be represented by CO_2 emissions, and in some cases GHG. Different types of assessment methods are available and applied in the studies, which can basically be divided into two major approaches: cost-based or impact weighing. The emissions are either applying a price tag (e.g. MILP model by Liotta et al. (2015)) or the impact of different types of emissions are weighted (e.g. Stated preference methodology, mode choice model by Patterson et al. (2008)) for optimisation, See Table 4. Air pollutants are significant emissions of transport (see Section 2.1) and are not always the co-benefit of CO_2/GHG (see Section 3.1) mitigation strategies as discussed. Their exclusion in transport mode selection, as reflected in Table 4, could lead to erroneous conclusions.

Most of the proposed optimisation models could be extended to cover more than CO_2 emissions. However, there is inherent difficulty to weight different types of emissions (other GHG and air pollutants) which have different impacts (climate change, haze/smog formation-visibility, human health etc), as also highlighted by Bauer et al. (2010). Data availability is also one of the reasons which contribute to the lesser consideration of air pollutants in freight transportation assessment. The implementation of carbon tax indirectly raises the research attention and facilitates assessment. Some of the studies (the 2nd and 3rd group in Table 4) did assess or optimise the emission of air pollutants. It is either non-simultaneous assessment (e.g. Table 4: Sunmi et al. (2004), Márquez and Cantillo (2013), Li et al. (2007), Tao et al. (2017)) or optimisation simply based on the emission criterion (e.g. Table 4: Yang et al. (2009), López-Navarro (2014) Park et al. (2007), You et al. (2010), Lee (2011), Bickford et al. (2013)).

The decision making on a sustainable transport mode cannot be selected based on environmental based criterion only. It should be a compromise solution that will benefit the different stakeholders. The most important mode choice variables/criteria are the cost and speed (transport time). The other criteria include the reliability (transit time), flexibility, safety, quality, noise and accident risk etc. Macharis et al. (2015) stated that the highest weights are allocated to transportation cost, reliability, flexibility, time and safety. A criteria selection in the perspective of transport provider for the reference shipment by Arencibia et al. (2015) illustrated that reliability (delivery time) is the most important criterion followed by cost and time. The criteria are not completely independent of each other due to the respective relationships that exist among them. The two representative fundamental types of criteria are transport expenses and transport time. It is also the most considered criteria in the transport mode assessment as summarised in Table 4.

This study has highlighted that a comprehensive assessment/optimisation method which does not compromise environmental issues (especially pollutants emissions) and is feasible for implementation (considering the criteria of the customer, logistics provider, and company etc) requires more development. In considering air pollutants, the account of impacts from the secondary pollutants can lead to a better decision making. Most of the presented studies in Table 4 utilised the emission factor to obtain the input data for optimisation. The advantages and disadvantages were discussed in Section 3. Lee (2011) applied microscopic traffic models instead of an emission factor. The dispersion model, however, did not include the secondary pollutants. Bickford et al. (2013) include CO_2 and the ambient air quality (including chemistry and complex meteorology) but the suggested modal shift could not be readily implemented due to the omission on the concerns of different stakeholders (other criteria).

4. Way forward

Simultaneous assessment of GHG and air pollutants is challenging due to their different impacts on the environment and having different atmospheric lifetime. GHG is the main contributor to climate change and air pollutants threaten human health. The further interaction of air pollutants in the atmosphere contribute to the formation of haze/smog as well as acid rain. Including air emission components with the other critical criteria in the selection of transport mode is rather complicated. Multi-criteria optimisation has been commonly applied to overcome the difficulty in evaluating the criteria with different impacts (as discussed in Section 3.2). The weighting factors assigned based on expert's judgement or survey (Table 4) experiences a certain level of uncertainty. This approach relies naturally on the weighting impact. The chosen weighting factors significantly influence the results or solutions.

The question remains in the conflict situation, for example, to select a solution with lower CO_2 (GHG) emission or lower SO_x (air pollutants) emission? How to achieve a feasible (cost, time etc) freight transport mode or system with low air emission? This might not be a significant issue for the supply chain study without considering different transport modes. For example, optimising the distribution route by using a truck. There are no contradicting results, where route A has a lower GHG emission than route B but higher in air pollutants emission. However, it is important for the study where only the departure and arrival location are fixed (modal shift, intermodal, multimodal). As the ratio of GHG and air pollutants across various transport modes are different (e.g. ship vs truck). GHG and air pollutants should be considered in an overall system towards a real sustainable solution, as also pinpointed by EEA (2013). The impact classification needs more studies as air pollutants have more than one impact compared to GHG with the main impact on climate change. The current LCA impact categories with the endpoint protection of human health, ecosystem and resource area proposed to have it in the air, water, land/soil. The suggestion is on the basis of preventing double counting and facilitate simultaneous assessment of air emissions.

Table 4
The transport mode selection studies with the consideration of environmental sustainability: Criteria and approaches.

Reference	Type of optimisation/ Assessment	Mode	Criteria							Environmental/Green Criteria	
			C/P	T/S	Cap.	Freq.	Flex.	R	Q	Type	Quantification (Emission)
Hoen et al. (2014)	Inventory model	Air, road, rail, water	✓	✓						CO_2	Cost (Network for transport and environment method)
Zhang et al. (2013)	Bi-level programming	Road, rail, inland	✓							CO_2	Cost (Range of prices)
Lam and Gu (2016)	Bi-objective optimisation model	Rail, truck, sea (Intermodal)	✓	✓						CO_2	Amount (as constraint)
Le and Lee (2013)	MP model	Truck, ship, air (Multimodal)	✓	✓						CO_2	Amount (EF-distance)
Liotta et al. (2015)	MILP model	Road, rail, sea (Multimodal)	✓	✓	✓					CO_2	Cost (EF-distance based on Ministry, French + cost based on Government of Canada)
Regmi and Hanaoka (2015)	Stated preference methodology, mode choice model	Road, rail (Modal shift)	✓	✓				✓		CO_2	Amount (EF-activity based)
Guo et al. (2016)	Evolution-strategy-based memetic Pareto optimisation model (multi-objective memetic optimisation approach)	18 transport modes with 3 different time	✓	✓						CO_2	Amount (EF fuel consumption)
Patterson et al. (2008)	Stated preference methodology, mode choice model	Rail and truck (Intermodal)	✓	✓	✓				✓	CO_2	Amount, (EF distance & traffic estimates)
Kim and Van Wee (2014)	Semi. LCA, comparative analysis	Rail, truck, sea (Intermodal)	✓	✓	✓					CO_2	Amount (EF-distance)
Soysal et al. (2014)	Multi-objective LP	Road, sea (Multimodal)	✓	✓						CO_2	Amount (EF-fuel consumption)
Macharis et al. (2015)	Combined multi-criteria decision analysis (AHP and PROMETHEE methods), GIS	Sea, road, rail (Unimodal, Intermodal)	✓	✓				✓	✓	CO_2, noise hindrance	Amount (EF-distance)
Highlight the application/Inclusion of GHG and/or air pollutants											
Qu et al. (2016)	Computational, Linear mixed integer program, Bi-criteria analysis	Truck, rail, sea (Intermodal, unimodal)	✓		✓					GHG (Case study is CO_2)	Cost (EF-distance + cost based on World Bank)
Bauer et al. (2010)	Computational	(Intermodal)	✓	✓						GHG (Case study is CO_2)	Amount (EF-activity-based)
Comer et al. (2010)	Geospatial network optimisation model	Road, rail, sea	✓	✓	✓					Emission (Case study is CO_2)	Amount (EF-activity based) least emission function etc
Yang et al. (2009)	Mobility Kaya Equation	Road, rail, sea, other subsectors								GHG	Amount (EF-energy consumption)
López-Navarro et al. (2014)	Comparative analysis (based on Marco Polo calculator)	Sea, road (Multimodal)								CO_2 + air pollutants, noise etc	Amount (distance); External cost (Macro polo calculator).
Park et al. (2007)	Compare (emission impacts analysis)	Road, rail (Intermodal, unimodal)								Air pollutants	Amount (EF-activity based)
You et al. (2010)	Compare	Road, rail								Air pollutants (PM, NO_x)	Amount (EF-distance + Traffic simulation)
Lee (2011)	Compare	Road, rail								Air pollutants	Amount (Microscopic traffic models, no secondary pollutants)
Bickford et al. (2013)	3D Eulerian photochemical transport model (Community Multiscale Air Quality Model, CMAQ) + Weather Research and	Truck, rail (Modal shift)								Air pollutants	Emission impact (WIFE, Wisconsin Inventory of Freight Emissions)

(*continued on next page*)

Table 4 (*continued*)

Reference	Type of optimisation/ Assessment	Mode	Criteria							Environmental/Green Criteria	
			C/P	T/S	Cap.	Freq.	Flex.	R	Q	Type	Quantification (Emission)
	Forecasting Model (WRF)										
Non-simultaneous assessment/optimisation (Environmental criterion is measured after the selection)											
Sunmi et al. (2004)	Logit models	Road, rail, sea (Multimodal)	✓	✓						CO_2	Amount (EF-distance)
Márquez and Cantillo (2013)	Demand model	Road, rail, river	✓	✓				✓	✓	CO_2, air pollutants	Amount (EF-distance)
Li et al. (2007)	Time value model (mode choice)	Road, rail (Intermodal)	✓	✓		✓				CO_2	Amount (EF-distance)
Tao et al. (2017)	Stated preference methodology, RCL model	Road, rail (Multimodal)	✓	✓						CO_2	Amount (EF-freight turnover, energy consumption per turnover)

EF = Emission Factor, C=Cost, P=Price, T = Time, S=Speed, Cap. = Capacity, Freq. = Frequency, Flex. = Flexibility, R = Reliability, Q = Quality, MP = Mathematical Programming, MILP = Mixed Integer Linear Programming, AHP = Analytic Hierarchy Process, PROMETHEE= Preference Ranking Organisation Method for Enrichment Evaluations.

The cost-based model has the limitation in expressing the need for mode shift. The pricing of the negative externalities per transportation mode has been presented by Demir et al. (2015). There are also several databases by countries/assessment tools (e.g. Marco Polo calculator and Network for transport and environment listed in Table 4 and GAINS (IIASA, 2017)) that provide the price of air emissions. This could facilitate the optimisation by including not only CO_2 emissions as most of the presented model (Table 4) can be extended. However, Hoen et al. (2014) stated that the impact of emission-related charges has an insignificant effect for a decision maker to select a different transportation mode or system. This highlights the weakness of a cost-based model in enhancing the environmental awareness and making a green decision. The destructive impacts of air emissions are not well reflected by the price. The cost-based assessment could also be affected by fluctuations resulting in under or over pricing and inappropriate alternatives. This study proposes the possibility of simultaneous assessment (GHG and air pollutants) through considering the energy required for the emissions removal. The energy required for carbon emissions sequestration or removing the air pollutants can be used as the unified unit and indicator for optimisation. This could overcome the fluctuations of cost-based assessment as well as impact weighting assessment which are subjective and rather qualitative. For example, published data exist on the energy required for carbon emissions sequestration, ranging from 0.135 kWh/kg to (David and Herzog, 2000) 0.462 kWh/kg of CO_2 captured (Ranjan and Herzog, 2011). However, large-scale experiments, further data collection and studies on the pros and cons are needed towards the methodology development. The proposed energy-based methodology for simultaneous assessment of GHG and air pollutants could have the similar weakness as cost-based assessment where the value fails to reflect the negative impacts on the environment. The research gaps to be filled and the potential improvement have been suggested towards a more specified sustainable transport mode.

5. Conclusion

This study has highlighted the importance of including air pollutants rather than limiting the focus on GHG emissions, particularly in the activities related to supply chain with different modes of transportation. The challenges or limitations of the current assessment and assessment model have been discussed. The selected transport could have a low GHG emission but it is not always an optimised solution when air pollutants are considered. The amount of emissions in transporting the goods is depending on the transport mode, fuel type, carrying capacity and the transporting distance. For example, from Rotterdam to Genoa, the travel distance of sea transport are approximately 4 times longer than road transport. The GHG emission of ships is lower than trucks but the PM (94.13 g/t vs 22.45 g/t) and NO_x (4,051.89 g/t vs 1,299.62 g/t) emission are higher. The SO_x emissions of ships are lower than trucks when low sulphur diesel is considered. However, a large proportion of the ships are not following the stringent standard (e.g. SECA). The assessment is more complicated for the route from non-EU to EU countries where the different fuel emission standards are applied. Future studies are needed to understand the relationship between the pollutants to have a representative impact category, the quantification unit as well as methodology development for assessment. Assessment of air emissions should be considered in an overall system. The proposed approach for simultaneous assessment is by considering the removal mechanism (the energy needed for GHG sequestration or mitigating the air emissions). The suggestion is based on the identified limitation of weighting and cost-based optimisation. This study serves as a stepping stone to developing an improved methodology that considers GHG-air pollutants nexus for an environmentally sustainable transport mode system with the minimal potential of footprint shifting. The proposed alternatives have to be feasible for implementation by including the other critical criteria than solely the environmental criterion.

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